

Explanation for the low flux of high energy astrophysical muon neutrinos

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We consider the possibility that some exotic neutrino property is responsible for reducing the muon neutrino flux at high energies from distant sources; specifically, we consider : (i) neutrino decay and (ii) neutrinos being pseudo-Dirac particles. This would provide a mechanism for the lack of high energy muon events in the Icecube detector.

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I. INTRODUCTION:

The most recent data from the Icecube collaboration[1] place stringent limits on the muon neutrino flux at high energies from astrophysical sources. The new limits put severe bounds on models of neutrino production in GRB's and AGN's[2].

In this note we would like to raise the possibility that the small flux is due to depletion of muon neutrinos which in turn is caused by neutrino properties.

We consider two possible scenarios. One is that neutrino decay is responsible for depletion of muon-neutrinos and the other is that neutrinos are pseudo-Dirac particles and there is leakage into the sterile components of the pseudo-Dirac particles. Both of these were considered almost ten years ago[3, 4], but the focus then was on the modification of the flavor mix from the canonical 1:1:1 as expected from conventional flavor oscillations with the known neutrino mixings[5]. In the following, we describe both possibilities. To be definite, we are considering neutrino energies in the vicinity of order of a PeV, and the distances from the sources of order of hundreds of megaparsecs. In principle, when the distances become large enough, the cosmological red shift becomes important, and the travel distance L is limited; these effects were discussed some time ago in ref.[4, 6, 7] and more recently in ref.[8] and ref.[9]

II. NEUTRINO DECAY:

The only neutrino decay modes which can be relevant for the short lifetimes of interest here are the invisible modes, essentially the decays into a neutrino and a spinless boson, as discussed in ref.[3, 10]. The current limits on the lifetimes of the three mass eigenstates are as follows. The most stringent is on that of ν_1 , from the observation of neutrinos from SN1987A as being about $\tau_1/m_1 > 10^5 s/eV$ [11]. The limits on the other two mass eigenstates are: $\tau_2/m_2 > 10^{-4} s/eV$ from the solar neu-

trino observations[12] and $\tau_3/m_3 > 10^{-10} s/eV$ from the atmospheric neutrino observations[13]. Obviously, the limits on the lifetimes of ν_2 and ν_3 are quite weak. For definiteness we assume the normal hierarchy, (there is no strong suppression of any one flavor in case of inverted hierarchy).

We consider that the source distances are large enough so that two of the three mass eigenstates specifically ν_2 and ν_3 have decayed away completely.

We assume that ν_2 and ν_3 decay into the lightest state, namely ν_1 . We assume that m_3 and m_2 are much larger than m_1 , that is there is no quasi-degeneracy. This is so as to ensure that the final state ν_1 has energy low enough that it does not contribute to the flux. Alternatively, one can consider decay into a sterile neutrino which serves the same purpose. The flavor content of ν_1 is $e : \mu : \tau = |U_{e1}|^2 : |U_{\mu 1}|^2 : |U_{\tau 1}|^2$ as observed long ago[14] and that is the flavor content of the beam that reaches us. If we insert the current best fit values for the MNSP elements[15], we find that $|U_{\mu 1}|^2$ ranges between 0.1 and 0.25 with a central value of about 0.14. The value of the phase δ in the MNSP matrix determines the precise value. This is a suppression beyond the factor of two due to the standard flavor oscillations. Thus, a suppression of the muon neutrino flux by an order of magnitude is easily achieved. Since the value of $|U_{e1}|^2$ is between 0.65 and 0.72, the ν_e flux is not affected much by the decays of ν_2 and ν_3 . We note in passing that the flux ratio of ν_e to ν_μ is between 3 and 7, depending on the value of the phase δ .

Amongst other consequences, the neutrino counting in early universe is modified from a count of 3 to $3 + 4/7$ due to the extra bosonic degree of freedom.

The bottom line is that if neutrinos decay, substantial reduction in ν_μ fluxes is possible, and consistent with ν_1 being the lightest mass eigenstate.

III. PSEUDO-DIRAC NEUTRINOS:

If each of the three neutrino mass eigenstates is actually a doublet with very small mass difference (smaller than $10^{-6}eV$), then there are no current experiments that could have detected this. Such a possibility was raised long ago[16]. It turns out that the only way to detect such small mass differences in the range ($10^{-12}eV^2 > \delta m^2 > 10^{-18}eV^2$) is by measuring flavor mixes of the high energy neutrinos from cosmic sources.

Let $(\nu_1^+, \nu_2^+, \nu_3^+; \nu_1^-, \nu_2^-, \nu_3^-)$ denote the six mass eigenstates where ν^+ and ν^- are a nearly degenerate pair. A 6X6 mixing matrix rotates the mass basis into the flavor basis $(\nu_e, \nu_\mu, \nu_\tau; \nu_e, \nu_\mu, \nu_\tau)$. In general, for six Majorana neutrino, there would be fifteen rotation angles and fifteen phases. However, for pseudo-Dirac neutrinos, Kobayashi and Lim[17] have given an elegant proof that the 6x6 matrix V_{KL} takes the very simple form

$$V_{KL} = \begin{pmatrix} U & 0 \\ 0 & U_R \end{pmatrix} \cdot \begin{pmatrix} V_1 & iV_1 \\ V_2 & -iV_2 \end{pmatrix}. \quad (1)$$

where the 3x3 matrix U is just the usual mixing matrix; the 3x3 matrix U_R is an unknown unitary matrix and V_1 and V_2 are the diagonal matrices $V_1 = \text{diag}(1, 1, 1)/\sqrt{2}$, and $V_2 = \text{diag}(e^{-i\phi^1}, e^{-i\phi^2}, e^{-i\phi^3})/\sqrt{2}$ with the ϕ_i being arbitrary phases.

As a result, the three active neutrino states are described in terms of the six mass eigenstates as:

$$\nu_{\alpha L} = U_{\alpha j} \frac{1}{\sqrt{2}} (\nu_j^+ + i\nu_j^-). \quad (2)$$

The nontrivial matrices U_R and V_2 are not accessible to active flavor measurements. The flavor conversion probability can thus be expressed as

$$P_{\alpha\beta} = \frac{1}{4} \left| \sum_{j=1}^3 U_{\alpha j} \left\{ e^{i(m_j^+)^2 l/2E} + e^{i(m_j^-)^2 l/2E} \right\} U_{\beta j}^* \right|^2 \quad (3)$$

In the description of the three active neutrinos, the only new parameters are the three pseudo-Dirac mass differences, $\delta m_j^2 = (m_j^+)^2 - (m_j^-)^2$. In the limit that they are negligible, the oscillation formulas reduce to the standard ones and there is no way to discern the pseudo-Dirac nature of the neutrinos.

Incidentally, the effective mass for neutrino-less double beta decay is given by

$$\langle m \rangle_{eff} = \frac{1}{2} \sum_j U_{ej}^2 (m_j^+ - m_j^-) = \frac{1}{2} \sum_j U_{ej}^2 \frac{\delta m_j^2}{2m_j} \quad (4)$$

The value of this effective mass is smaller than $10^{-4} eV$ and renders neutrinoless double beta decay unobservable.

When L/E becomes large enough, flavor fluxes will deviate from the canonical value of $1/3$ by[4]

$$\delta P_\beta = \frac{1}{3} [|U_{\beta 1}|^2 \chi_1 + |U_{\beta 2}|^2 \chi_2 + |U_{\beta 3}|^2 \chi_3] \quad (5)$$

where $\chi_i = \sin^2(\delta m_i^2 L/4E)$

We assume that for the neutrinos from distant sources arriving in Icecube, $\chi_1 \approx 0$ but $\chi_2 = \chi_3 \approx 1/2$; i.e. $\delta m_1^2 \ll \delta m_2^2$ and δm_3^2 .

The deviation from $1/3$ for ν'_μ s is given by

$$\delta P_\mu = -\frac{1}{3} \left[\frac{1}{2} (|U_{\mu 2}|^2 + |U_{\mu 3}|^2) \right] \quad (6)$$

Using the current best values for the mixing parameters[15], this can be very close $1/6$, thus giving an extra reduction by a factor of 2 for the flux of ν'_μ s. In a model for pseudo-Dirac neutrinos via Mirror-world, a further suppression by a factor $1/2$ obtains resulting in a net suppression by a factor of $1/4$ [18]. Furthermore, the shift in P_e from the value $1/3$ is about 0.8, and so the ratio ν_e/ν_μ is about 3.

This is a very different physics possibility from the decay case but also gives rise to low fluxes of ν_μ s consistent with the lack of observation in Icecube.

IV. SUMMARY

To summarize, we raise two rather different possibilities of neutrino properties which can account for the low fluxes of ν'_μ s at high energies, and give rather large values for the ratio of ν_e to ν_μ fluxes. The two can be distinguished in several ways. The decay changes the primordial neutrino counting from 3 to $3+4/7$, and the pseudo-Dirac neutrinos make the neutrinoless double beta decay unobservable. Only further experimental data can confirm or rule out these speculations. Since the scenarios considered here do not suppress the electron neutrino flux, we have no problem with the shower events reported by Icecube at the Neutrino 2012 meeting in June [19].

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